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The Rise and Fall of American Technological Leadership: The Postwar Era in Historical Perspective

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I. *Introduction*

DURING THE QUARTER CENTURY following World War II, the United States was the world's most productive economy by virtually any measure. U.S. output per worker was higher by margins of 30 to 50 percent over the other leading industrial nations, and the gap in total factor productivity was nearly as large (Edward Denison 1967). These differences held not just in the aggregate but in almost all industries (David Dollar and Edward Wolff 1988). Many factors lay behind the U.S. edge, but it seems evident that the country's position of world leadership in advanced technology was an important one. The U.S. technology lead was partly reflected in the productivity statistics but is not the same thing. On the one hand, measured total factor productivity is affected by many elements, command over technology being only one of them. On the other hand, the productivity measures fail to reflect the fact that American output included sophisticated goods that could not be produced abroad. While in this essay we sometimes use productivity data as part sometimes use productivity data as part of the evidence about technological leadership, our concern is with the latter rather than the former. A wide variety of measures, backed by the commentary of informed observers, provides solid evidence that during the period in question the U.S. technological lead was real. U.S. firms were significantly ahead in developing and employing the leading edge technologies, their exports accounted for the largest share of world trade in their product fields, and their overseas branches often were dominant firms in their host countries.

No longer. The U.S. technological lead has been eroded in many industries, and in some the U.S. is now a laggard. A growing volume of studies, books, commission reports, and popular media accounts bemoans this loss of leadership and looks for causes and cures (e.g., Michael Dertouzos, Richard Lester, and Robert Solow 1989; James Womak, Daniel Jones, and Daniel Roos 1991). This paper is motivated by the apparent weakening, perhaps loss of American technological leadership, but more basically by the observation that relatively little of the current discussion is informed by an understanding of the sources of America's unique position in the mid-twentieth century economic world. How can policies respond appropriately to "what we have lost" without a clear knowledge of what it was that we had and how we got it?

However, the questions of how the postwar American lead came about, and how and why it has eroded, pose deeper questions in turn. There has in recent decades been a striking convergence among the most advanced industrial nations in per capita income, and in output per man hour, both in the aggregate and in a wide spectrum of industries (Figure 1). This phenomenon has spawned a thriving new literature on "convergence"

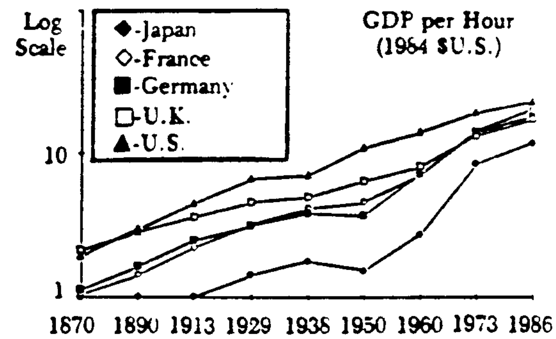

Figure 1. Gross Domestic Product per Hour, 1870–1986

Source: Angus Maddison (1987, 1989)

(Moses Abramovitz 1986; William Baumol 1986; J. Bradford De Long 1988; Dollar and Wolff 1988; Baumol, Sue Anne Batey Blackman, and Wolff 1989; Robert Barro 1991). While a portion of the analytic apparatus and a few of the ideas in this recent literature are new, the general questions being explored have been around for a long time. Historical economists have long been interested in why Britian forged ahead of the Continent in the new technologies of the first industrial revolution, and the process through which other economies later caught up (Bernard Elbaum and William Lazonick 1986). More generally, how can one explain why certain countries take a significant technological lead in key industries in certain eras, and maintain it for some time? How do other countries catch on? Is convergence really the dominant process over long epochs, with history punctuated from time to time by new leadership surges from formerly backward nations? If so, why the "punctuations"?

But these questions pose still deeper ones. In what sense can one talk about "national" technological capabilities? In what ways do borders and citizenship matter? What is the role of the nation-state in technological development, and has this role changed historically? Is the recent trend to convergence mainly an equilibration process among nations, or is it a sign of decline in the importance of nationalities and borders?

As we see it, the recent literature on these topics contains three broad perspectives, often implicit. One, associated with the convergence literature, sees the U.S. postwar lead as inherently transient, attributable partly to the late start of many of our present rivals, and partly to the destruction of our major industrial rivals during the war; convergence was therefore relatively automatic and inevitable. A second view sees not convergence but rather U.S. industry losing out in a competitive struggle with other national industries. In this view, the United States is now falling below the pack of leading countries as England did a century ago, with Japan and perhaps Germany taking on new leadership roles. The authors of this school vary in the reasons they stress. For Paul Kennedy (1987) it is the burden of defense spending. For Christopher Freeman (1987), Michael Piore and Charles Sabel (1984), James Womack, Daniel Jones, and Daniel Roos (1991), and Lazonick (1990), relative U.S. decline reflects the rise in other nations of new and better ways of organizing aspects of economic activity, with the U.S. stuck in its old ruts. A third interpretation posits a more fundamental decline in the role of national borders and nationally based industrial centers. Convergence has occurred, in this view, but not simply as a result of postwar recovery or international technological diffusion and imitation, or the rise of superior new national systems. Rather, the argument is that just as markets and business have become more global, the network of individuals and organizations generating and improving new science-based technologies have become less national and more transnational, so that convergence reflects a diminution of the saliency of nation-states as technological and economic entities.

We do not claim that these three frameworks are neatly distinguishable, and we certainly do not claim to have answered our own questions definitively. But we believe there is value in posing these questions carefully and clearly, and we attempt to marshal analysis and evidence bearing on them. This we have tried to do in the context of the U.S. experience, within the limits of our own competence and the space allocated by the *Journal*.

Let us tip our hand by stating where we come out on some of the critical issues. First, the U.S. lead of the early postwar era was not merely a temporary result of the war but stemmed from two relatively distinct sources. Part of the lead reflected long standing American dominance in mass production industries, which in turn derived from uniquely favorable historical access to natural resources and to the world's largest domestic market. The other part of the American lead, in high technology industries, was new, and reflected the massive private and public investments in R&D and scientific and technical education that the United States made after World War II. Though these investments built on older institutional foundations, broadly based world leadership by the United States in basic science and in technologies drawing on new scientific frontiers was largely a postwar development. Thus, there were two components to U.S. leadership, and they have weakened for conceptually different but institutionally connected reasons. Growing domestic markets outside the United States, and the opening of the world as a common market in resource commodities as well as consumer and producer goods have virtually eliminated the advantages American firms used to have in mass production. And as the networks of technological development and communication have become more oriented to professional peer-group communities, which have themselves become increasingly international, technology has become more accessible to companies that make the requisite investments in research and development, regardless of their nationality. Increasingly, such investments have been made by firms based in other countries. These developments are associated with the fact that large industrial firms are increasingly transnational. Where national industries become tradition-bound and fall behind, international convergence is still advanced by the migration of capital, management, and personnel across international borders. The net result of these developments is a world in which national borders and citizenship mean significantly less technologically than they used to.

Our discussion is organized as follows. We begin by examining the rise of American strength in the mass production industries during the nineteenth century, considering especially the reasons why American technology came to differ from, and in an important sense to surpass, that of the Europeans. We also describe the rise during the early twentieth century of the American chemical and electrical products industries. Then we turn to the interwar period when the U.S. consolidated its lead in mass production and laid the basis for its advances in "high tech" after World War II, by establishing a solid base in organized research, and by providing the experience of post secondary education to a broad segment of the population. Then we consider the early postwar era, focusing particularly on how U.S. primacy was achieved in such fields as microelectronics. Finally, in light of our analysis of the nature of U.S. leads in mass production and high tech, and the factors that maintained the U.S. advantages, we present our diagnosis of how and why the twin leads have declined since the late 1950s, and our views of what might lie ahead.

II. *Long Standing American Strengths*

In this section we deal with that part of the American postwar lead in manufacturing that had been there for a long time: mass production industries. We shall distinguish the reasons for the U.S. advantage in these industries rather sharply from the factors behind U.S. dominance after World War II in fields like semiconductors and computers. But before we get into the discussion of American leadership in mass production, it is important to consider the senses in which we can talk at all about national technological capabilities. What does it mean to say that (firms in) one country has a technological lead over (firms in) other countries?

A. *National Technologies and Technological Leadership*

If technology were a pure public good, as economists are wont to assume in elementary versions of microeconomic theory, then the proposition that firms in certain countries are able to employ technologies that lie beyond the ken of firms elsewhere would make no sense. The input and output mixes of firms located in different countries might be different, but such divergence would merely reflect differences in market or other environmental conditions that influence what firms choose to do. Thus during the nineteenth century the special U.S. conditions of cheap resources, high wage rates, and large markets, could be understood to induce the high labor productivity, large-scale, capital-intensive production methods that became known as characteristically American. But the contrast with European practice would be ascribable entirely to economic choices rather than to differences in the technology choice set.

Of course economists have long recognized that firms are sometimes able to bar others from using their technology through threats of a patent infringement suit, or by tightly held trade secrets. But there is little evidence that patent suits were effective barriers to technological transfer in the metal working and mass production industries where nineteenth-century American firms achieved their greatest advantage. Some American firms certainly tried to guard key trade secrets, but high interfirm mobility among technically informed personnel made firms into relatively leaky institutions for technical information that could be carried in the heads of knowledgeable individuals. Just as British restrictions in an earlier era did not stop Samuel Slater and a host of followers from carrying their understanding of textile technology across the Atlantic (David Jeremy 1981), American firms of the late nineteenth and early twentieth centuries were seldom able to block technological secrets from international dissemination.

Nonetheless we argue that the concept of a "national technology" is a useful and defensible analytical abstraction, appropriate for much of modern history if decreasingly so in recent times. Our proposition rests on three intertwined arguments. First, the technologies in question were complex, involving different kinds of machines and a variety of learned skills, and often requiring relatively sophisticated coordination and management. While certain features of these complex operations were described in writing, or more generally were familiar to the experts in the field, to get the technologies under control and operating well generally required a lot of learning-by-doing on the part of many interacting people, from engineers to managers to machine operators, as well as investment in plant and equipment. Thus "technology transfer" involved much more than what one or a few men could carry away in their heads, or in a few drawings or models. These could provide a start on technology transfer but real command of the technology required a considerable amount of trial-and-error organizational learning. Thus the technology was not really a public good in the standard sense. American firms had a command of it that others did not, and could not master without significant time and effort.

Second, to a considerable extent technical advance in these fields was local and incremental, building from and improving on prevailing practice. The knowledge useful for advancing technology included, prominently, experience with the existing technology so as to be aware of its strengths and weaknesses, and to know how it actually worked. Thus those at the forefront of the technology were in the best position to further advance it. Economic historians have long been aware of this kind of technological learning. Nathan Rosenberg (1963) recounts the evolution of American machine-tool technology in the nineteenth century as a sequence of problem solving challenges. At any given point, progress was constrained by a particular bottleneck known mainly by those experiencing it, yet each new solution shifted the focus to another technical constraint or phase of production. With frontier technology rapidly changing and new applications being spun off, physical presence in the active area was virtually indispensable for anyone who hoped to improve on the prevailing best-practice.

Third, sustained technological advance was not the result of one person or firm pushing things ahead, but involved many interacting people and firms. One learned from another's invention and went a step further. Robert C. Allen (1983) describes this process of "collective invention" in some detail, in his study of British Bessemer steel producers in the Cleveland district, and Elting Morison (1974) describes a similar process among American Bessemer producers. The interdependencies went well beyond mere aggregation of achievements over time. As demonstrated in Ross Thomson's account of the origins and diffusion of the sewing machine (Thomson 1989), the success of new technical breakthroughs required that they mesh with prevailing complementary technologies, and that they fit into a complex chain of contingent production and exchange activities, from raw material to final distribution. Any number of *technically* successful mechanical stitchers had been invented in the 60 years prior to Elias Howe's officially recognized invention of 1846, but none succeeded commercially. Howe's machine did succeed, because it fit in with complementary technologies and skills, and because it initiated a process in which new firms formed nodes in a communication network linked to other innovators. In turn, the principles and the networks of interdependence that came out of sewing machine development became applicable to a host of related industries.

In short, technological progress is a network phenomenon replete with "network externalities" of the sort that have now come in for intensive theoretical scrutiny (Michael Katz and Carl Shapiro 1985), by *path-dependence*, i.e., dependence of successive developments on prior events (Paul David 1975, 1988; Richard Nelson and Sidney Winter 1982), and a tendency for particular systems to become "locked in" beyond a certain point (W. Brian Arthur 1988, 1989). A striking historical feature of these networks of cumulative technological learning is that down to recent times their scope has been largely defined by national borders. Why should this have been so?

In the first place, for reasons of geographical proximity. The networks described by Allen, Morison, and Thomson all involved inventors and tinkerers living in the same general area and having intimate contact with each others' inventions if not each other. Second, to the extent that technological communications networks follow in the tracks of previously established linguistic and cultural communities, it would be entirely natural for technologies to have something of a national character. Such a primary basis might well be reinforced by the existence of centralized or uniform national institutions for technical training, though this was a less striking feature of American development than it was in European countries like France and Germany. Even in the absence of officially mandated uniformity, however, American scientists and engineers displayed early signs of national identity, rooted in the distinctness and commonality of their problem solving environment: the resource base, the product market, and the legal/institutional conditions were markedly different from those in European countries. The key elements of such networks are common terms and reference points, methods of measurement, and standards of technical performance. A Scottish visitor during 1849–50 complained that American mineralogists disdained to label their formations with the names of European localities, but insisted on an independent national terminology. Nathan Rosenberg (1985) points out that most of what we now call science-based progress did not deploy "frontier" scientific concepts, but involved largely mundane and elementary tasks, such as grading and testing of materials, for which scientific training was needed but where the learning was specific to the materials at hand. Standardizing such measurements, and physically embodying them in instruments and apparatus (as well as procedures) were among the main tasks of the distinctly American scientific and engineering associations which emerged in this country at the end of the nineteenth century (Edward Constant 1983). Critics of American capitalism complain that by the 1920s, American engineers themselves had become standardized commodities, through the close links between corporations and institutions of higher education (David Noble 1977). As the American technology was by that time the envy of the industrial world, however, aspiring young engineers could hardly have done better than to gain the training that would give them access to the national technological network.

Of course not all countries had such indigenous national technological communities, for reasons of scale, political stability, or historical accident. We do not address ultimate questions of historical economic development in this essay, but focus instead on the narrower task of describing the emergence of a distinctive American technology from the end of the nineteenth century onward, and tracing the course of that national characteristic in the twentieth century.

B. *The Rise of Mass Production in the Nineteenth Century*

American technology began to make a splash in the world at least as early as the mid-nineteenth century. Mechanical reapers, mass-produced firearms, and many other American novelties created a noticeable stir at the Crystal Palace Exhibition in London in 1851. In this early period, however, the impressive technical achievements of the "American System of Manufactures" pertained only to a small subset of industries, while in other major areas (such as iron-making) the U.S. was clearly behind European countries (John James and Jonathan Skinner 1985).

Nonetheless, across the nineteenth century the country did develop the sine qua non for advanced technological status, an indigenous technological community able to adapt European techniques to American conditions. Though the process of technological search was decentralized and competitive, flows of information through trade channels, printed media, and informal contacts served to establish a distinctive American problem solving network. An important early institutional manifestation was the emergence of a specialized machine-tool industry, which evolved from machine shops linked to New England textile mills in the 1820s and 1830s and became a "machinery industry" generating and diffusing new technologies for a wide range of consumer goods industries (Nathan Rosenberg 1963). Economic historians have traced remarkable threads of continuity in the histories of firms and individual machinists, as steady improvements in machine speeds, power transmission, lubrication, gearing mechanisms, precision metal cutting, and many other dimensions of performance were applied in one industrial setting after another: textiles, sewing machines, farm machinery, locks, clocks, firearms, boots and shoes, locomotives, bicycles, cigarettes, sewing machines, and so on (David Hounshell 1984; Thomson 1989). This distinctively American development represented a type of collective learning, which fed into the twentieth century technologies that formed the basis of U.S. world leadership.

By the end of the nineteenth century, American industry assumed a qualitatively different place in the world. A number of important innovations concentrated in the 1880s took advantage of the opportunities for mass production and mass marketing offered by the national rail and telegraph networks. These included new branded and packaged consumer products (cigarettes, canned goods, flour and grain products, beer, dairy products, soaps and drugs); mass-produced light machinery (sewing machines, typewriters, cameras); electrical equipment; and standardized industrial machinery such as boilers, pumps, and printing presses (Alfred Chandler 1990, pp. 62–71). Although most of these products were developed for the domestic market, many of them became exports as well. The first wave of alarmist European books on "Americanization" dates from 1901 and 1902, with titles and themes about an "American invasion" which would again became familiar in the 1920s and 1960s (e.g., Frederick MacKenzie 1901). Particularly noteworthy were growing American exports of industrial machinery, farm equipment, hardware and other engineering goods, producers' goods which embodied mass-production principles and which in many cases posed a new competitive challenge abroad. In addition, by 1900 the American steel industry had become a world leader, and the country was exporting an extensive array of iron and steel products (Allen 1977). This international standing was new. Prior to the 1890s, American steel rails would not have survived in the domestic market without tariff protection (Allen 1981).

These new turn-of-the-century achievements may be thought of as the confluence of two technological streams: the ongoing advance of mechanical and metal-working skills and performance, focused on high-volume production of standardized commodities; and the process of exploring, developing, and utilizing the mineral resource base of the national economy. As surprising as it may seem from a modern perspective, the rise of American industry to world leadership was intimately connected with the rise of the country to world leadership in the production of coal, iron ore, copper, petroleum, and virtually every other major industrial raw material of that era. To cite one important example, the breakthrough in the steel industry coincided with the opening of the rich Mesabi iron range in the 1890s, and to concomitant adaptations in technology and transportation (Allen 1977). Analysis of trade in manufactures reveals that intensity in nonreproducible resources was one of the most robust characteristics of American goods, and this relative intensity was in fact *increasing* across the critical period from 1880 to 1930 (Wright 1990). Louis Cain and Donald Paterson (1986) find that material-using technological biases were significant in nine of twenty American sectors, including those with the strongest export performance.

It would be a mistake to imply that the country's industrial performance rested on resource abundance and scale economies *as opposed to* technology, because mineral discovery, extraction, and metallurgy drew upon, stimulated, and focused some of the most advanced engineering developments of the time, as did mass production. The U.S. Geological Survey was the most ambitious and successful government science project of the nineteenth century, and the country quickly rose to world leadership in the training of mining engineers (David and Wright 1991). New processes of electrolytic smelting and refining had a dramatic impact on the industrial potential of copper, nickel, zinc, and aluminum. The oft-noted complementarity between capital and natural resources in that era was not merely an exogenous technological relationship, but may be viewed as a measure of the successful accomplishment of a technology in which Americans pioneered. Mass production industries were also intensive in their use of fuels and materials. Not only did the capital stock itself embody domestic materials, but "high-throughput" methods, to maximize the sustainable rate of capacity utilization, imply high ratios of physical materials and fuels to labor. For these reasons, although they were highly profitable given the economic conditions in the United States, American technologies were often not well adapted to other localities. Robert Allen (1979, p. 919) estimates that in 1907–09 the ratio of horsepower to workers was twice as large in America as in either Germany or Great Britain. On the other hand, American total factor productivity in this industry was only about 15 percent ahead of Great Britain, and approximately equal to that in Germany. This statistic does not imply that German steel makers could have matched American labor productivity levels "simply" by operating at the American level of capital and resource intensity. Our central point is that there is nothing "simple" about the processes through which firms come to adopt and learn to control technologies that have been in use elsewhere for some time. Rather, the numbers illustrate the particular kinds of new technological developments that the Americans developed. Accounts of the course of technological progress in Germany suggest an entirely different orientation governed by "the desire to find substitutes for expensive and uncertain imports" (Peter Hayes 1987, p. 1).

American manufacturing firms and their technologies not only were resource and capital intensive, but operated at much greater scale than did their counterparts in the United Kingdom and on the Continent. Large scale operation was well tuned to the particularities of the large affluent American market. By 1900 total national income in the United States was twice as large as that of the U.K., about four times as large as France or Germany. Per capita income had also surpassed that of Great Britain and was well ahead of continental Europe. American language and culture were reasonably homogeneous, and internal transportation and communications systems were well developed. Perhaps because of their relative freedom from traditional class standards, American consumers readily took to standardized products, a development which came much later in Europe. Further, this large American market was effectively off limits to European producers because of high prevailing levels of tariff protection. Although the size of the U.S. domestic market may have been partially offset by the greater relative importance of exports for the European countries, foreign markets were highly diverse and much less receptive to standardized goods than they later became. Oriented mainly toward the domestic market, American firms tended to produce a narrow range of product specifications. In the steel industry, for example, though the U.S. was dominant in mass-produced products, in specialty steels the U.S. performance was "a story of false starts, technological backwardness, commercial failures, and continued dependence on foreign steel" (Geoffrey Tweedale 1986, p. 221). American harvesting machinery and locomotives (like automobiles at a later point) were technically impressive but inappropriate for most of the world's markets. Many European engineers held a low opinion of their American counterparts, for emphasizing production and speed over quality and durability (Daniel Headrick 1988, pp. 75, 84).

It has often been argued that the distinctive strength of American corporations lay less in technology per se than in organizational efficiencies associated with mass production and mass distribution. The success abroad of the Singer Sewing Machine Company, for example, was not based on highly sophisticated product design or factory technology, but in the efficiency of its production, sales, and service organization (Fred Carstensen 1984, p. 26). Singer's ventures abroad came relatively early; but in general, the interest of American firms in foreign markets emerged belatedly, only after they had established national distribution networks (Mira Wilkins 1970). Here again, we should not think of organizational strength as an *alternative* but as a complement to advanced technology. As Alfred Chandler has argued, modern corporate enterprise tended to arise in sectors which had undergone prior technological transformation, and the new organizational form served to make more effective use of these new technological possibilities (Chandler 1977). Chandler's new comparative work, *Scale and Scope*, emphasizes that the United States had far more of these new technically and managerially advanced corporate institutions much earlier than any other country. Chandler's account of the "organizational capabilities" within large American firms is compelling and persuasive, but we would place more emphasis than he does on system-wide features of the economy, and on the ongoing development of the technology itself. The large American companies were not just efficiently streamlined organizations; they were part and parcel of an emerging technological and managerial network, engaged in a collective learning process with a strongly national character. By the late nineteenth century the management style in American manufacturing companies had become very different from that in Great Britain and continental Europe.

The concept and practice of "professional management" first arose in the United States, and by 1900 it was common for a large American firm to be staffed by a cadre of professional, educated, middle managers, a phenomenon that seems to have been almost exclusively American. In his recent book, Lazonick (1990) argues that American management increasingly took control of the job floor at this time, in contrast to Britain, where management had little control over the details of work. The "scientific management" movement was singularly American, and closely associated with the professionalization of management. In a fascinating recent paper, Kogut (1992) stresses the importance of basic principles of management and organization, which he argues take on a strikingly national character, or at least used to. He proposes that it was the style of management and organization, far more than the simple economies of scale and scope, that led to the pre-eminence of American corporations in the early years of the twentieth century, although the former was essential to the latter. In his empirical examination of American corporations that establishes overseas branches, Kogut found many large companies, but also some middle-sized ones. Almost all of them, however, were marked by strong adherence to the management and organizational principles described above, which formed a distinctly American style.

We note here that relatively little of the American performance during this era was based in science, nor even on advanced technical education. American technology was practical, shop-floor oriented, built on experience. The level of advanced training in German industry was substantially higher (Jürgen Kocka 1980, pp. 95–96). As prominent an American engineer as Frederick W. Taylor, who played a major role in developing high-speed tool steel years before he invented "scientific management," had only an undergraduate degree and was deeply skeptical of the practical value of university training. The search for valu-

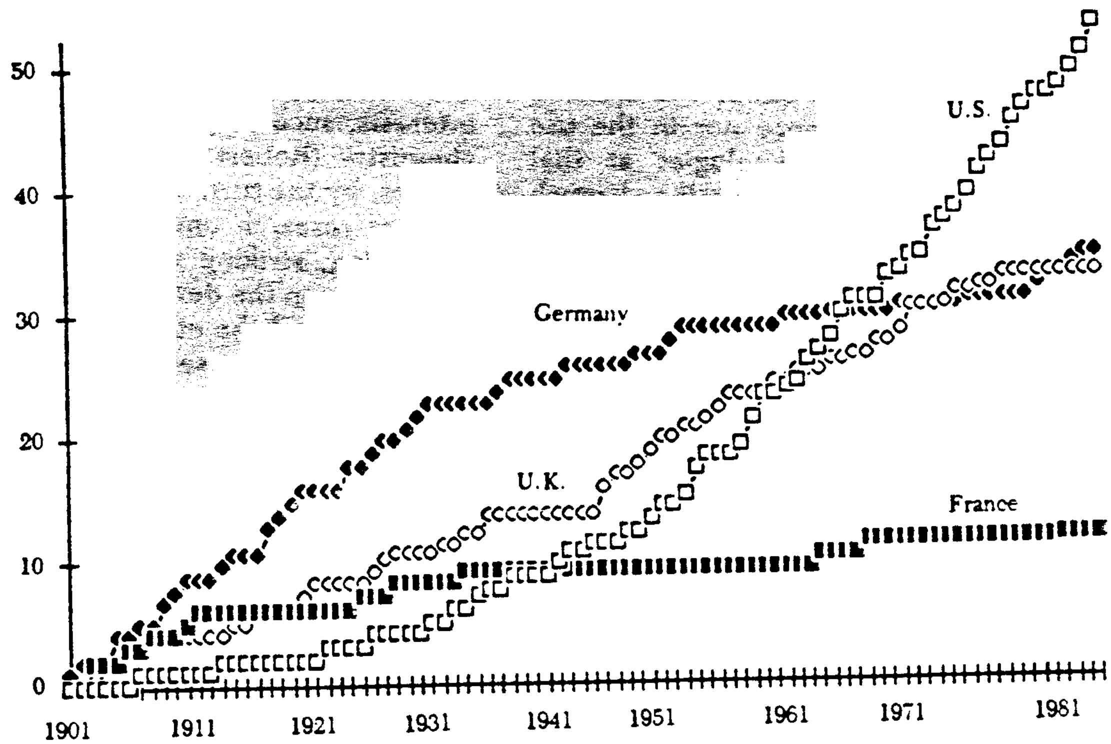

Figure 2. Cumulative Nobel Prizes in Physics and Chemistry, 1901–1990

able petroleum by-products was carried out by people with only a smattering of chemical education (Nathan Rosenberg 1985, p. 43). Many of the industries in which American strength was clearest and strongest, such as nonelectrical machinery, steel, and vehicles, were distinguished well into the twentieth century by an aversion to organized science-based research. American universities did have areas of strength in certain applied fields, but an aspiring student who sought the best available academic education in scientific disciplines like physics and chemistry would have been advised to study in Germany, Britain, or France. As Figure 2 shows, the U.S. did not surpass these countries in scientific Nobel Prizes until long after World War II.

These observations are intended to delineate rather than to downplay the magnitude of what American industry had achieved by the early 20th century. American firms were the clear leaders in productivity across the range of mass production industries. This lead in manufacturing combined with highly productive American agriculture to support wage rates and living standards higher than those in England, and higher still than on the Continent (Ernest Henry Phelps Brown 1973). In turn, high wage rates and living standards induced and supported large scale, capital- and resource-intensive production. And while the particular technologies and structures adopted by U.S. manufacturing firms reflected these unique aspects of the American scene, by and large where American industry went, Europe followed, if often with a pronounced lag.

C. *Building the Infrastructure for Science-based Industry*

By the start of World War I, the United States had established a position of leadership in mass production and mass distribution industries, a technology characterized by scale economies, capital intensity, standardization, and the intensive use of natural resources. Though the United States was not the world leader in science nor in the use of science-based technologies at that time, the country had developed much of the private organization and public infrastructure needed to operate effectively in the science-based industries that were coming into prominence.

Federal government support for university programs in agriculture and the practical arts dates from the Morrill Land Grant College Act of 1862. Though this act led directly to the founding of several major state universities and the strengthening of others, little significant research could be credited to it prior to the Hatch Act of 1887, which provided each state with funding for an agricultural experiment station. The level of support for research was doubled by the Adams Act of 1906, and unique institutions for the dissemination of knowledge among farmers were in place with the establishment of the cooperative extension service in 1914. At this juncture the U.S. was well behind Europe in the deployment of "scientific agriculture"—soil chemistry, plant biology, animal husbandry. But a generation later these investments in infrastructure had unprecedented payoffs in agricultural productivity.

The Morrill Act also provided a federal stimulus to engineering education; within a decade after its passage, the number of engineering schools increased from six to seventy, growing further to 126 in 1917. The number of graduates from engineering colleges grew from 100 in 1870 to 4300 at the outbreak of World War I (Noble 1977, p. 24). Like their agricultural counterparts, engineers and scientists at American universities were under continuing pressure to demonstrate the practical benefits of their efforts. "Merely theoretical" research was openly belittled, and the areas of applied science which did show some strength in the nineteenth century were mainly those linked to state-specific economic interests, such as geology and industrial chemistry (Robert Bruce 1987). Nonetheless, by the turn of the century a network of research universities had come into being, striking an institutional balance between the demand for immediate usefulness and the ethos of academic independence espoused by the emerging scientific disciplines. According to Roger Geiger (1986), the main elements in this balance were the provision of large-scale undergraduate teaching as a means of financing research and graduate training; and the successful mobilization of nationalistic sentiments in support of science. A watershed of sorts was passed with the founding of the American Association of Universities in 1900, to bolster academic standards, establish uniformity in requirements for the Ph.D., and achieve foreign recognition for U.S. doctorates. Though business-university cooperation has continued to be an important part of American technological history, the prospect of world-class research universities came only after a certain social distance from industry had been established.

At the same time, American industry was building its own technological infrastructure. In the wake of the great merger wave in American business (1897–1902), which established many of today's well-known corporations in positions of national market power for the first time, an unprecedented expansion of private-sector research laboratories occurred, a trend that accelerated over the next half-century (Figure 3). General Electric, DuPont, AT&T, and Kodak all set up formal research laboratories before World War I. Here too, the lasting institutional implications may have been very different from the original motivations of

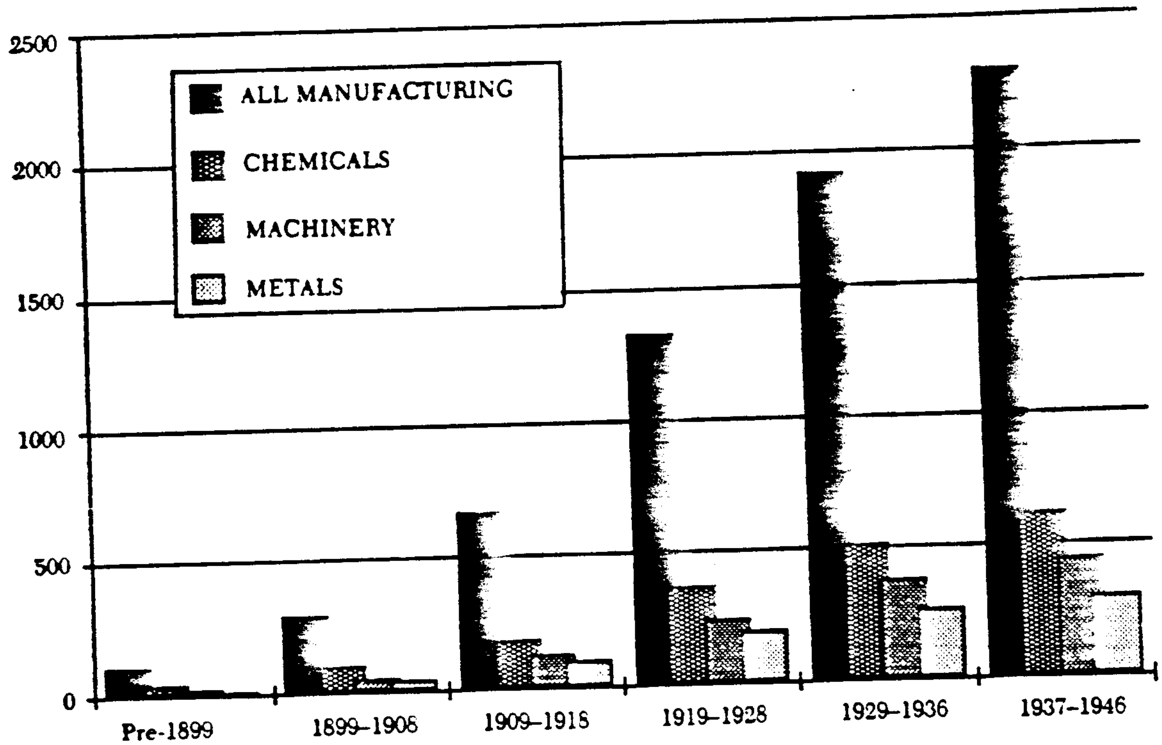

Figure 3. Laboratory Foundations in U.S. Manufacturing

Source: David Mowery and Nathan Rosenberg (1989, Table 4.1)

the founders. Business historians have argued that these early firms were not looking to do pioneering research in new technologies, but to control innovation and protect an established patent position (Leonard Reich 1985; John Kenly Smith 1990). Once established, however, a science-based research tradition evolved, often with considerable autonomy from the immediate objectives of the employer.

Only in chemistry had there been any substantial use of scientifically trained personnel prior to 1900. In 1875 the Pennsylvania Railroad hired a Yale Ph.D. chemist to organize a laboratory for testing and analysis of materials brought from suppliers. As Nathan Rosenberg argues, much of the early use of science by industry was of just this sort, a relatively mundane application of laboratory procedures for testing materials, well within the frontiers of existing science. Institutionalizing such procedures, however, often led to unexpected results. The Pennsylvania Railroad laboratory, for example, went on to develop an improved lubrication composition for locomotives. A Ph.D. chemist hired by the Carnegie Steel Company not only helped to identify high quality ores, but found ways to make better iron and steel. Increasingly, chemists came to play an important part in technological innovation in iron and steel making, in traditional inorganic chemicals like soda, and in new organic chemical substances like dyes and later plastics.

The German chemical industry unquestionably was the leader in dyestuffs, plastics, and other new products based on organic chemistry. Christopher Freeman's data show that through 1945, I. G. Farben was by far the largest patentor in plastics. By 1910 or so, however, the leading American companies like Du-

Pont, Dow, and Kodak had established R&D laboratories and had developed the capacity to produce a full range of industrial chemicals and a wide range of fine chemicals (Noble 1977; Hounshell and John Smith 1988). These companies were able to draw upon the newly emerging specialty of chemical engineering, an American professional hybrid. They were thus organizationally well positioned to take advantage of the cutoff of trade with the Germans during World War I, and to respond to the need to provide a variety of products for the military. The abrogation of German patents brought the American companies close to technological parity with the Germans by the 1920s.

The story in the new electrical industry is similar, except that here American strength was apparent somewhat earlier. As in chemistry, performance was clearly not rooted in any American advantage in fundamental science; U.S. universities were significantly behind those in Germany and other continental countries in teaching and research in physics. But American industry had early access to trained personnel in electrical *engineering*. By the last decades of the nineteenth century in universities like M.I.T. and Cornell, physics and mechanical engineering had been self-consciously combined as a field of training (Robert Rosenberg 1984). Thomas Hughes has argued that in the new electrical industries, the Americans excelled in the conception, design, development, and implementation of large scale systems (Hughes 1987). In addition, the U.S. industry benefited from scientifically educated European emigres like Thomson, Tesla, Steinmetz, and Alexanderson.

Here again one may see the influence of the large, affluent American market, not as an *alternative* to technology, but as an influence on the directions taken by American technology, and a source of unique advantages in international comparisons. There are numerous examples of innovations which were European in origin, but whose development progressed most rapidly in the United States because of the scale economies accessible in the American market (Hans-Joachim Braun 1983).

III. *The Interwar Period*

In the 1920s and 1930s, American industry consolidated its position of leadership in mass production industries, while joining these longer-term strengths to organized research and advanced training in important new industries such as chemical and electrical engineering. Some of the circumstances were historically fortuitous. The United States escaped damage and even enjoyed industrial stimulation from World War I. After the war, the institutions of international trade and finance remained in disarray, stumbling toward their complete collapse in the 1930s. Industrial countries that depended on foreign markets had a hard time of it (though Japan managed to continue its industrial growth despite these obstacles). American industries were largely insulated from these problems. The country was highly protectionist from the time of the Civil War. In the 1920s, despite the emerging strength of American industry, import barriers were increased, first by the Fordney-McCumber Tariff of 1922, and then by the notorious Hawley-Smoot Tariff of 1930. But the domestic market was more than sufficient to support rapid productivity growth and the ongoing development and diffusion of new technologies and new products.

A. *The Marriage of Old and New Industrial Strengths*

The automobile industry was the most spectacular American success story of the interwar period, a striking blend of mass production methods, cheap ma-

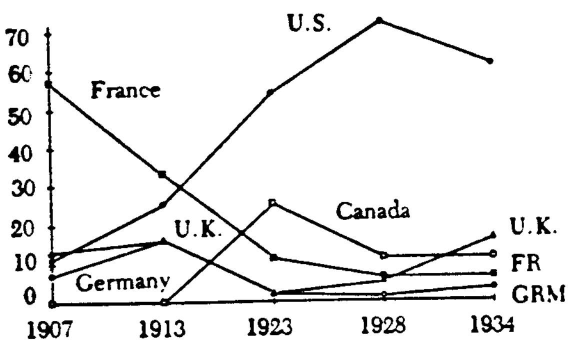

Figure 4. Shares of World Motor Vehicle Exports, 1907–1934

Source: James Foreman-Peck (1982, p. 868).

terials, and fuels. The distinct lead of American producers over French and British rivals really dates only from the advent of the assembly line at Ford between 1908 and 1913, but the ascendancy was rapid thereafter. Though the historical origins of this performance may be traced back to characteristics of the domestic market, the extent of American leadership is clearly indicated by the high volume of exports, notwithstanding the fact that the size and fuel requirements of American cars were poorly suited to foreign demand. Despite barriers to trade and weak world demand, U.S. cars dominated world trade during the 1920s, and motor vehicles dominated American manufacturing exports (Figure 4). Henry Ford's books were best sellers abroad, and "Fordism" developed a cult technocratic following in both Germany and the Soviet Union (Hughes 1989). The components of the U.S. cost advantage are difficult to measure with precision, however, because the large-scale auto firm came as a package: organizational, managerial, financial, and technological. The branch plants of American firms were also dominant abroad, though during the interwar period they were not fully able to replicate performance at home (Foreman-Peck 1982). The process of global diffusion and adaptation of American methods would surely have continued, however, either by imitation or by direct foreign investment, if it had not been interrupted by World War II.

In many ways a more lasting and significant basis for technological leadership was established in those industries that were able to marry mass production methods to organized science-based research, such as the electrical industries and chemical engineering. Though the fundamental scientific breakthroughs in electricity had come earlier, the interwar period saw the realization of this potential through full electrification of factories and households. Paul David (1989) has called attention recently to electrification as an example of an innovation whose productivity impact was delayed for a full generation, because of the need to disseminate and adapt the underlying knowledge, and to restructure physical plants and work routines. The percentage of factories using electric power grew from 25 in 1910 to 75 in 1930 (Warren Devine 1983), a development essential for the acceleration of productivity growth at this time. A similar infusion occurred in the household, where the use of electric lighting rose from 33 percent of urban families in 1909 to 96 percent in 1939 (Stanley Lebergott 1976). Large firms like GE, Westinghouse, and AT&T established advanced research organizations that generated an ongoing flow of innovative new electrical products, sometimes advancing the frontiers of science in the process.

The rise of chemical engineering was also a marriage of old and new strengths. Ralph Landau and Nathan Rosenberg (1990) point out that this professional category was an American innovation, combining chemistry with training in industrial processes. It was also relatively new, emerging as a course of study at MIT in the first two decades of the twentieth century, becoming a separate department only in 1920. The American surge was also closely associated with a shift in the basic feedstock for chemical plants from coal to petroleum, a primary product in which the U.S. dominated world production. As technology developed, the production of organic chemicals was carried on most effectively as a by-product of general petroleum refining, hence closely connected with the location of petroleum supplies. Prior to the 1920s, there was little contact between petroleum companies and the chemical industry. In that decade, however, important connections emerged, through mergers, research establishments, and industry-university associations. Working in close partnership with M.I.T., New Jersey Standard's research organization in Baton Rouge, Louisiana, produced such important process innovations as hydroforming, fluid flex coking, and fluid catalytic cracking (Landau 1990a). Here we have a remarkable blend of mass production, advanced science, and American resources. As the chemical engineer Peter Spitz has written: "Regardless of the fact that Europe's chemical industry was for a long time more advanced than that in the United States, the future of organic chemicals was going to be related to petroleum, not coal, as soon as companies such as Union Carbide, Standard Oil (New Jersey), Shell, and Dow turned their attention to the production of petrochemicals" (Spitz 1988, p. xiii). Petroleum led the way in the use of scientifically trained personnel in the first half of the century (Figure 5).

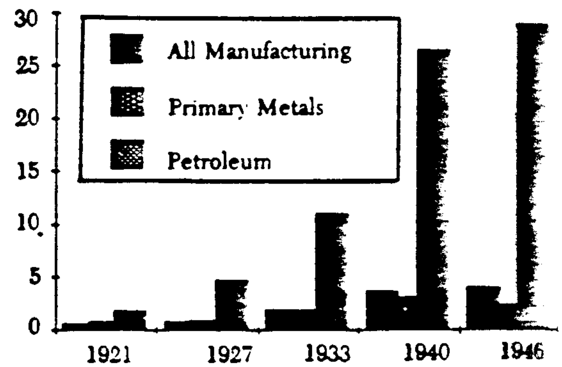

Figure 5. Scientists and Engineers per 1000 Wage Earners

Source: Mowery and Nathan Rosenberg (1989, Tables 4.2, 4.3, 4.4, 4.5, 4.6)

B. *Education and Technology*

Sooner or later, discussions of American industrial and technological performance generally come around to the educational system. Americans seem to believe in a golden age during which the country led the world in mass public schooling, and that this enlightened leadership in education was also closely associated with leadership in technology. There is some truth in this account, but the story is less straightforward than commonly imagined. It is true that the United States was an early leader in literacy and primary education, achieving close to universal elementary enrollment before the Civil War (outside of the South), well ahead of France and Britain (Richard Easterlin 1981). Only Germany (where in Prussia compulsory education dated from 1763) approached these levels. Because basic education has a clear effect on the capacity to conduct commercial operations and process written information (Theodore Schultz 1975), the diffusion of schooling among the American farming population undoubtedly had a positive influence on its responsiveness to new opportunities and its receptivity to innovations. But these benefits pertained largely to a population of farm proprietors, which for the most part was not the source of the labor for American factories during the country's surge to world industrial leadership. From the time of the Irish influx in the 1840s, the bulk of the industrial labor force came from immigration, mostly from non-English-speaking countries with far lower educational standards than those prevailing

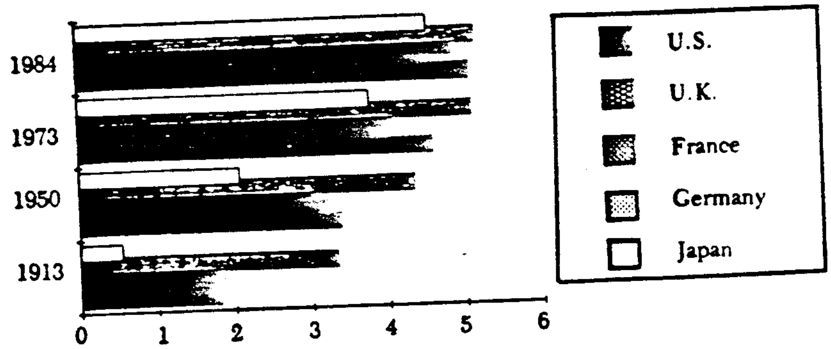

Figure 6. Average Years Secondary Education, 1913–1984 (Pop. 15–64)
Source: Maddison (1987, Table A-12)

among the native born. In 1910 the foreign born and the sons of the foreign born were more than 60 percent of the machine operatives in the country, and more than two-thirds of the laborers in mining and manufacturing (U.S. Senate 1911, pp. 332–34). There is no reason to believe that this labor force was particularly well educated by world standards. This may not have been a drawback. It has been argued that the workpace in American factories was uniquely high (Gregory Clark 1987), an intensity of effort that one might well associate with "high-throughput" production strategy, but not necessarily with high levels of education on the part of workers. To be sure, the educational background of overhead and administrative personnel undoubtedly contributed to rising productivity; but the combination of a well-educated staff at the top and hard-driving workers at the bottom is very different from the success formulas of today's world. The upgrading of educational standards for production workers came largely after the cutoff of immigration in the early 1920s.

Educational attainment did indeed increase rapidly, as much of the country moved towards the norm of a high school degree. As job qualifications were raised and mechanization tended to eliminate jobs requiring mere brute strength and exertion, it is reasonable to hold that higher educational standards contributed to the remarkable rates of productivity growth maintained by American industry between 1920 and 1960, though we have no detailed understanding of this process. It is appropriate to note, however, that the expansion of secondary education in the twentieth century was not particularly unique to the United States. Similar trends were recorded in virtually all of the "advanced" countries of the world, and as of 1950 there was no marked difference in average years of secondary education among the United States, France, and Britain, all of them still well behind Germany (Figure 6). This does not gainsay the contribution of secondary education to American performance, but it underscores the point that broadly based education contributes to technological leadership only as these skills are effectively utilized by industrial employers. The disrupted conditions of world trade between 1914 and 1950 very likely constrained many countries from exploiting their educational potential.

The respect in which the United States was distinct among the nations of the world was the percentage of the population gaining access to a college education (Figure 7). As early as 1890, the ratio of university students per 1000 primary students in America was two to three times

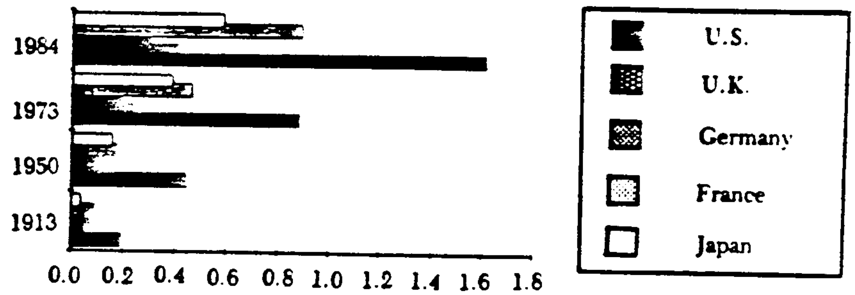

Figure 7. Average Years Higher Education, 1870–1984 (Pop. 15–64)
Source. Maddison (1987, Table A-12)

that of any other country, and this gap was maintained and increased through the period of American industrial ascendancy. After 1900, the surge in enrollment was particularly robust in applied sciences and engineering (Geiger 1986, p. 14); in new specialties like electrical engineering, American institutions such as M.I.T. were reputed to be the best in the world by World War I. Advanced training in business management also experienced rapid post-1900 growth (Chandler 1990, p. 83). Though university-trained engineers, scientists, and managers were no more than a small percentage of those employed in American industry, here if anywhere is a specific institutional basis for American technological leadership. Utilization of such personnel grew steadily through the twentieth century (Mowery and Nathan Rosenberg 1989).

So also did employment of college-trained people in a wide range of activities ancillary to R&D and production. Employment in marketing, accounting, legal service, finance, insurance, and communications grew rapidly over the interwar period, some of it in manufacturing firms, some of it in other sectors. By and large American organizations were able to tap a more highly educated population for these jobs than their European counterparts.

There are reasons to believe that the numbers somewhat exaggerate the American educational advantage "at the top." The elite grammar schools of the United Kingdom, the gymnasium of Germany, and the lycée of France, tended to teach subjects beyond what was taught in all but the best American high schools, and Americans graduating from high school tended to be younger and to have fewer years of education than their European counterparts coming out of the secondary institutions listed above. A number of commentators (e.g., Geiger) have noted that American university faculty often complained that their students were far less educated when they came to university than were students entering university in Europe. However, particularly with the advantage of hindsight, it is clear that long before the Europeans, Americans developed a tradition where a significant fraction of the sons (and later the daughters) of middle class families went on to education beyond high school. And the American middle class wanted "practical education."

Though the significance of university education for technology may seem self-evident, we have to acknowledge that we lack a clear understanding of the specific linkages. As with education more generally, what is important is not the sheer number of students or the quantity of their training, but the effectiveness with which that training is integrated into the process of improving the technology of operating firms. In interwar America that coordination was advanced to a high state of refinement, as the curricula of educational institutions came to be closely adapted to the requirements of the "positions" that graduates would be taking; and vice versa (Lazonick 1990, pp. 230–32). A 1921 survey made note of the "progressive dependence [of corporations] upon higher education institutions as sources of employee supply . . . the prejudice of many businessmen to higher education as a factor in employment is being rapidly overcome" (quoted in Noble 1977, p. 243). Political critics have complained that the process of national standardization in the specifications for products and processes came to be extended to personnel, as engineers "automatically integrated professional requirements with industrial and corporate requirements" (Noble 1977, p. 168). In 1919, for example, MIT launched its Co-operative Course in electrical engineering, a program that divided the students' time between courses at the Institute and at General Electric, which hired one-half of the students after graduation. The program was later joined by AT&T, Bell Labs, Western Electric, and other firms (Noble 1977, p. 192). Whatever the merits of Noble's reservation about the close links between universities and private firms, what he describes is an effective network of training and utilization, operating efficiently at a national level because it was self-contained, internalizing the resource base and market demands of the national economy.

We have noted that in recent years a sizeable literature on economic "convergence" has emerged, oriented around the proposition that large technological gaps between countries, and the associated gaps in productivity and income, are not sustainable if the lagging countries have the requisite "social capabilities." Abramovitz (1986) has suggested that these include, prominently, a well-educated work force including competence at the top in the major sciences and technologies of the era, adequate firm management and organization, and financial institutions and governments capable of keeping their fiscal and monetary houses in order. It is arguable that during the interwar period the major European economies were not significantly outmatched by the United States in these dimensions, although we have highlighted some important differences. It is noteworthy, however, that there was little if any tendency toward systematic convergence in command of mass production technologies during this period, nor in levels of labor productivity and per capita income relative to the United States. Although general dispersion narrowed, the mean productivity of Maddison's fifteen successful countries was no higher in 1938 as a percentage of the U.S. level than it had been in 1929, 1913, or 1890 (Abramovitz 1986, p. 391).

There are a number of reasons. One was the chaotic economic climate that affected most economies over this interval. Indeed Maddison's data show a sharp drop in the growth of world exports from nearly 4.0 percent per year between 1870 and 1913, to about 1.0 percent per year on average between 1913 and 1950. The average ratio of merchandise exports to GDP in the countries he examined fell from 11.2 percent in 1913 to 8.3 percent in 1950, and the number was almost certainly even lower during the 1930s. Thus during the interwar period nations were even more self-contained than they had been in the thirty years or so before World War I, and far more so than they became after World War II. This meant that the mass production methods used by American producers, which were highly productive and efficient on the

American scene, were less attractive to European firms facing their own home markets. Convergence is far from an automatic phenomenon. It requires not only that the lagging nations have requisite social capabilities, but also that their firms face an economic and political environment conducive to adopting technology used in the leading country. Rather than refining procedures for testing the "convergence hypothesis" as a universal tendency, it seems more fruitful to examine the new features of the postwar era that have encouraged and facilitated convergence among the world's leading countries.

IV. *The Postwar Era: The American Breakaway at the Technological Frontiers*

Just as after WWI, the United States came out of WWII buoyant, with technological capabilities extended by wartime production experience, while Europe came out prostrate. In contrast to the 1920s, after WWII Japan too was a demolished economy and nation. By the mid 1950s, most of the war-devastated countries had regained and surpassed prewar productivity and income levels, but as Figure 1 shows, the U.S. productivity and income edge remained enormous. While some Europeans seemed surprised at the lead of the Americans even after European recovery, they should not have been. The U.S. productivity lead in general, and in mass production industries in particular, had been around since the turn of the century. What was new was U.S. dominance in the "high technology" industries of the postwar era. Several intertwined but distinguishable reasons lay behind this development.

A. *National Technology and National Leadership in Science-based Fields*

Like the mass production technologies, newer "science based" technologies are advanced through community efforts. But to a far greater extent, chemical and electrical technologies, and nowadays fields like aircraft and semiconductors, require university-trained scientists and engineers, engaged in teamwork aimed to achieve new and better production process designs, through activities that have come to be called research and development. As a result, possession of university training, and involvement in organized R&D define the relevant technological communities.

Put another way, in science-based technologies the skills and experience needed to advance a technology include much more than can be acquired simply by working with that technology and learning from experience. In some cases the two components are completely disjoined. A chemist working on a new drug in a laboratory owned by a pharmaceutical company may know little about how pharmaceuticals are produced or even how the drug works on the human body. In other cases both kinds of understanding are needed. Thus a chemical engineer working on a way to produce a new plastic must know both standard production practice and a lot of formal chemistry. If the two types of understanding are separated too widely, problems of execution can easily result. But whatever the optimal mixture or practice, the industries in which the U.S. forged ahead after World War II required experience, specialized training, and organized research and development for effective advancement of the technology.

How then did the U.S. achieve its new lead in high technology industry? By investing more than other nations in training scientists and engineers, and in R&D in these technologies. The groundwork for these massive investments had been well laid earlier. We have described the rise of industrial R&D, and the rise of higher education. By World War II the U.S. had a number of world class firms in science-based industries, and several universities doing world class research. But the U.S. was not dominant in high technology industries.

B. *The Surge of Investment in R&D*

World War II changed the context. Victory brought a new sense of confidence and pride in America's strength, an awe for the power of science and technology engendered by their role in winning the war, and a burning belief in their capabilities for opening new horizons for the future. The write-ups of wartime science clearly were designed to kindle this appreciation on the part of the public (e.g., James Baxter 1946). Vannevar Bush's *Science, The Endless Frontier* (1945) gave the trumpet call, and the United States was off to levels of investment in science and technology that were historically unprecedented.

Before the war Americans had on average roughly double the years of post-secondary education as did the Europeans, although as we have noted the statistics may exaggerate the actual size of the educational gap. Between 1950 and 1973 the average number of years of American post-secondary education again doubled, further widening the gap. In part this was a simple consequence of affluence and a belief in the value of education. But the trend was also strongly encouraged by government policies. The G.I. bill of rights, which guaranteed educational funding to all qualified veterans, was both emblematic and an important factor in its own right. College fellowships became available through a number of other public programs. The state-supported part of the American higher education system provided significant additional funding and subsidy. Only a relatively small share of the new wave of university students went into natural science and engineering. But the sheer numbers meant that there was a large increase in the supply of trained scientists and engineers.

The expansion of supply was also supported, and in part propelled, by major increases in demand, from several sources. A small but important fraction was employed by the rapidly expanding U.S. university research system. The scientists and engineers who had engaged in the war effort had striking success in their argument that university science warranted public support, and during the half decade after the war the government put into place machinery to provide that support. The new research support programs of the National Science Foundation and the National Institutes of Health provided public funding of university basic research across a wide spectrum of fields. However, the bulk of government support for university research came not from these agencies but from agencies pursuing particular missions and using university research as an instrument in that endeavor. Thus, the Department of Defense and the Atomic Energy Commission provided large scale research funding in fields of particular interest to them. And the support was not just for basic research. These agencies funded research that involved applied science and engineering departments in work at the forefront of technologies in materials and electronics. By the middle 1950s the American research universities clearly were ahead of those in the rest of the world in most fields. Just as young American scholars flocked to German universities to learn science during the late 19th century, so young students from Europe, Japan, and other parts of the world came to the United States for their training.

The largest share of the increased demand for engineers and scientists, however, came from a vast expansion in the number of American companies doing R&D and in the size of their R&D programs (Mowery and Nathan Rosenberg 1989). Figure 8 displays estimates of the

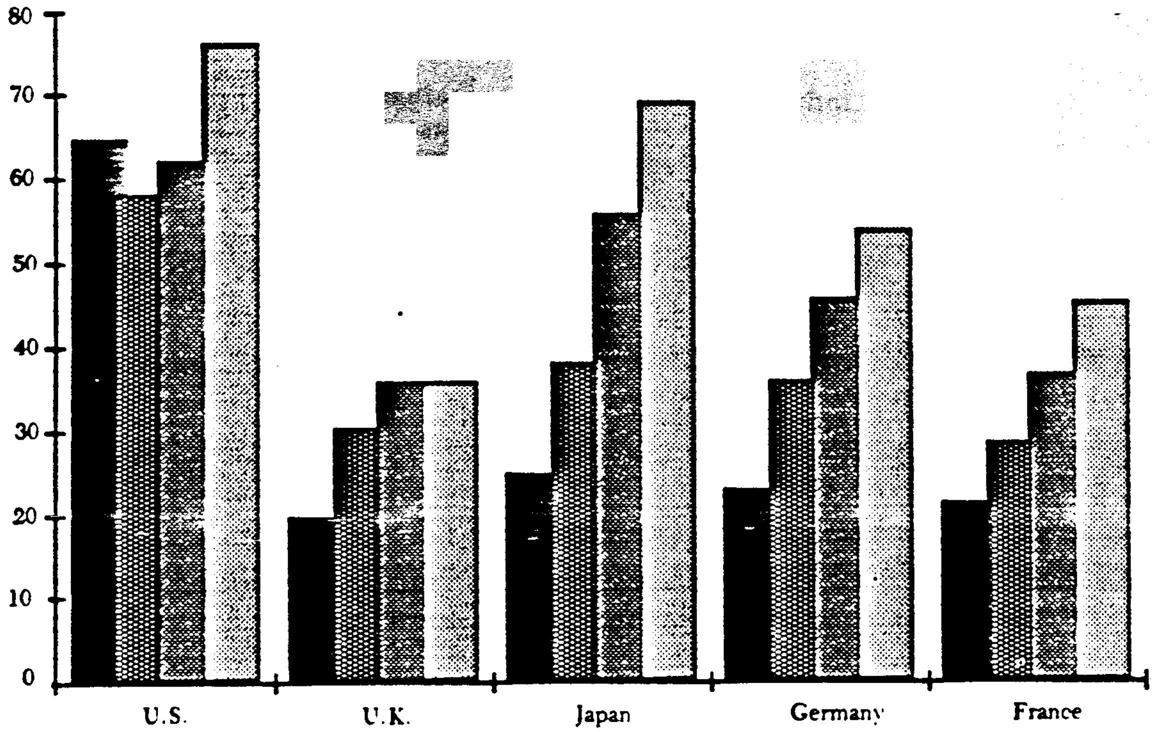

Figure 8. Scientists and Engineers Engaged in R&D per 10,000 Workers: 1965, 1972, 1981, 1987
Source: U.S. National Science Board, (1989 and 1991, Appendix Table 3–19).

number of scientists and engineers engaged in R&D (including corporate, university and other organizations) as a fraction of the workforce. Figure 9 shows the same phenomenon in terms of R&D as a fraction of GNP. Between 1953 and 1960 total R&D expenditures (in constant dollars) more than doubled, and the ratio to GNP nearly doubled. Employment of scientists and engineers in industrial research grew from fewer than 50,000 in 1946 to roughly 300,000 in 1962. Other countries lagged in increasing these kinds of investments. As late as 1969, total U.S. expenditure on R&D was more than double that of the U.K., Germany, France, and Japan combined. But by then the slowdown in U.S. productivity growth had already begun.

The R&D figures exaggerate somewhat the increase in investments in technical progress (Luc Soete et al. 1989). While formal R&D is the principal vehicle for technological advance in the science based industries, a good share of the work of improving manufacturing processes goes on outside formal R&D organizations, and often is not included in the R&D statistics. For example, a major part of improvement is often in design, usually done in an engineering department and often not counted as R&D despite the fact that it involves comparable activities. Many small firms engage in inventing, design, and development work without a formal R&D department and often without reporting any R&D. During the period in question the term R&D was becoming fashionable, and it is likely that a growing fraction of that work was so labeled. With all of these qualifications, however, it is clear that the increase in resources allocated to advancing technology was massive, and not matched in other countries.

The rise of corporate R&D in the U.S.

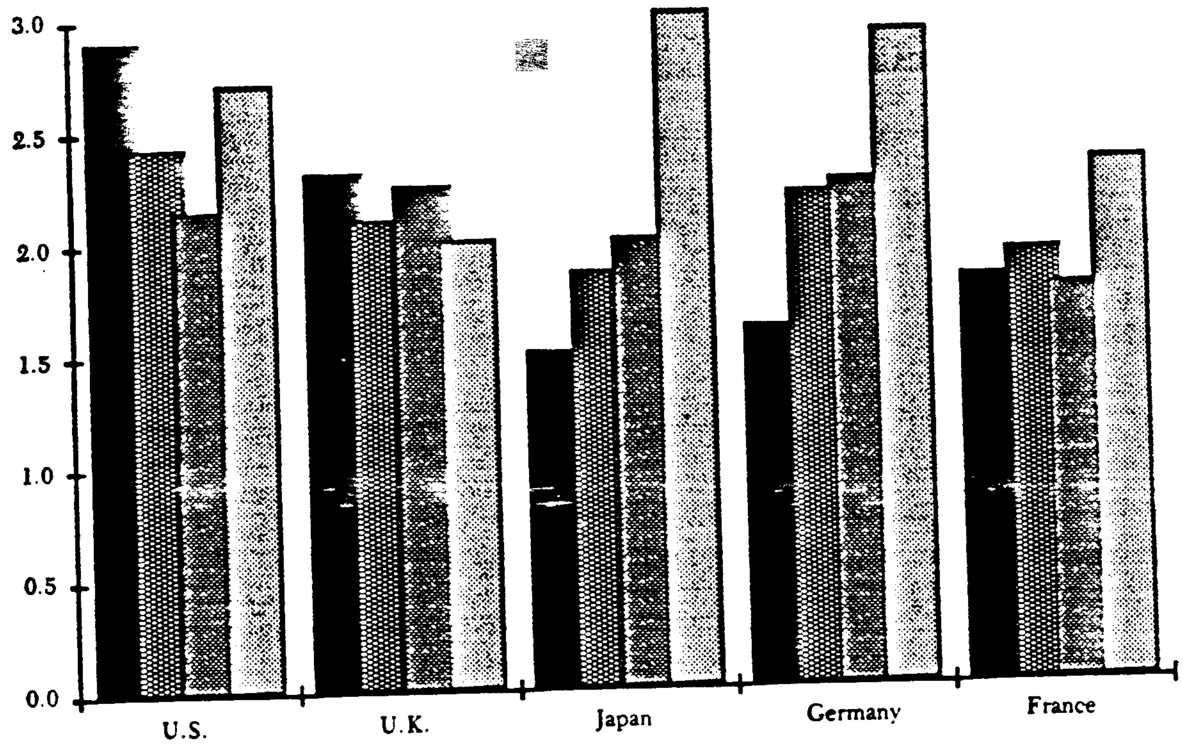

Figure 9. Expenditures for R&D as Percentage of GNP: 1964, 1971, 1978, 1989

Source: U.S. National Science Board (1989, Appendix Table 4–19; 1991, Appendix Table 4–26).

had two sources. Partly it was the result of major increases in private corporate R&D funding, based on optimistic beliefs in the profitability of such investments, a belief which by and large was well founded. Partly the rise came from large DoD, and later NASA, investments in new systems. In the mid 1960s private funds accounted for about half of corporate R&D, government funds the other half. In some industries, such as pharmaceuticals and other chemical industries, corporate funds provided almost all the support. In others, such as electronics, there was both strong private effort in such firms as AT&T and IBM, and large scale DoD funding. In industries like jet engines and space systems almost all the funding was DoD or NASA.

American dominance in computer and semiconductor technologies gained most European attention and concern during the 1950s and 1960s. These were considered the leading edge technologies of the era, and many foreign observers attributed the American advantage to defense support. Military and to a lesser extent space R&D support certainly was important. But military demands and money were going into an R&D system that was well endowed with trained scientists and engineers, had a strong university research base, and was populated with companies that were technically capable.

During the 1930s those concerned with the capabilities of the armed forces, both in Europe and the United States, were sharply aware of the advantages that could be gained by enhanced ability to solve complex equation systems rapidly. Ballistics calculations were perhaps the dominant concern, but there were others as well (Kenneth Flamm 1987; Barbara Katz and Almarin Phillips in Nelson 1982). Prior to and during World War II the German and British as well as the

U.S. funded research aimed at developing a rapid computer. It is clear enough that during and shortly after the war, by which time the feasability of electronic computers had been established, the United States vastly outspent other governments in bringing this embryonic technology into a form that was operational in terms of military needs. Several major research universities were involved in the effort, notably MIT. IBM and AT&T participated actively. Early assessments were that the nonmilitary demand for computers would be small. It was apparent by 1960, however, that nonmilitary demand would be large, and it also turned out that the design experience that the major U.S. companies had had in their work on military systems was directly relevant to civilian systems.

The story regarding semiconductors is somewhat different (Franco Malerba 1985; Richard Levin in Nelson 1982). Although military funds had gone into semiconductor devices during World War II, it was the Bell Telephone Laboratories that came up with the critical discoveries and inventions, using their own money, and motivated by the perceived technological needs of the telephone system. Once the potential had been demonstrated, however, the armed services, and later NASA, quickly recognized the relevance of the technology to their needs. Significant government R&D went into supporting technical advance in semiconductors and, perhaps more important as it turned out, the DoD and NASA signaled themselves as large potential purchasers of transistors. The evidence is clear that major amounts of private R&D money went into trying to advance semiconductor technology, in anticipation of a large government market. And in the field of semiconductor technology, as well as computer technology, design experiences with the transistors and later the integrated circuits that were of high value to the military set companies up to produce items for civilian products.

By the mid 1960s the American lead in the new high technology industries, like the old lead in mass production industries, was widely taken as a fact of life, a source of pride for Americans, and of concern to Europeans, but not readily subject to change. Jean Jacques Servan Schreiber pointed to the U.S. lead with alarm, arguing that if Europeans did not act quickly to catch up, they would be permanently subservient to the Americans. His diagnosis of the sources of American strength was rich and complex, if in places ironically amusing in the face of subsequent developments. He pointed not only to American investments in R&D and in science and engineering education, but to the overall quality of the American workforce, its willingness to cooperate with management, and the skill, energy, and willingness to take risks that he believed characterized American management.

In its famous "technology gap" studies, the OECD provided a more systematic, nuanced, and variegated diagnosis. The OECD argued that there was little that American scientists and engineers knew that good Europeans ones did not know also. The "gaps" stemmed mainly from management and organization, and experience, just as we have stressed. Technology is partly in books and mind, partly in the fingers and organization. The information part is largely a public good for those with the requisite training and experience. But the latter part involves significant firm specific investment and learning. Ironically, just at the time when American dominance was most visible, conditions were changing to undermine its sources. By the 1960s the U.S. lead was shrinking, both in the areas of longstanding strength, and in the new high technology fields.

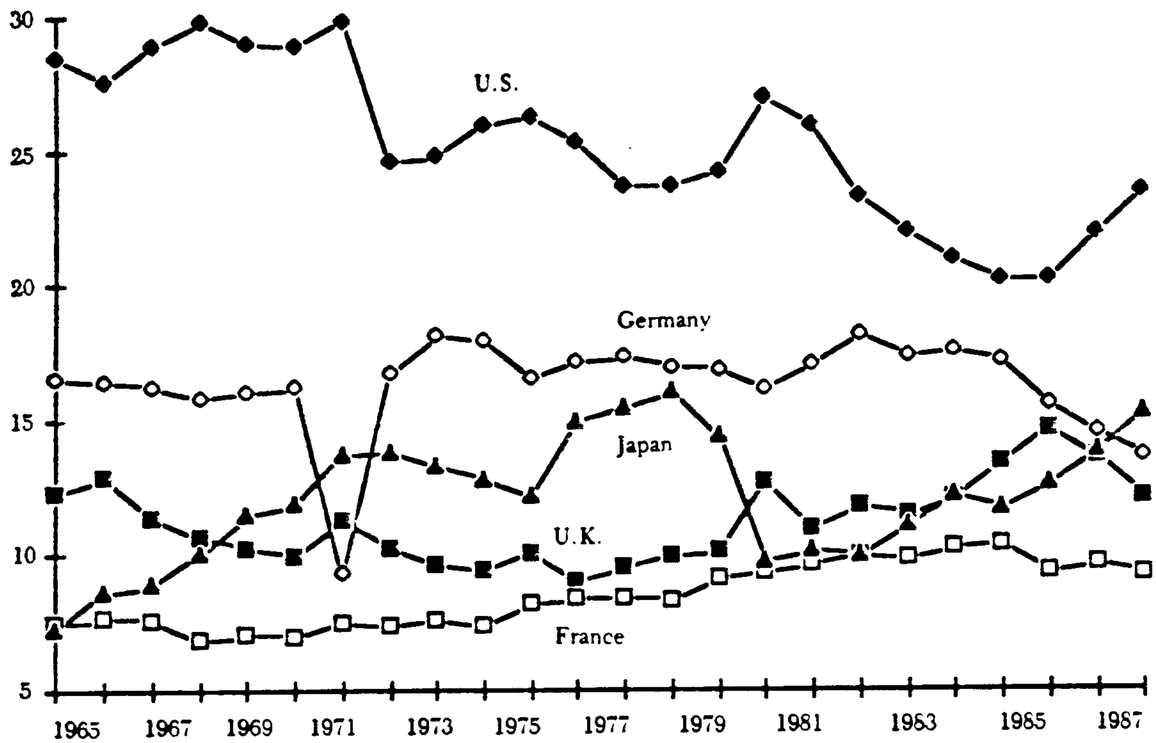

Figure 10. Country Shares of World High-Technology Exports, 1965–1988

Source: U.S. National Science Board (1987, Appendix Table 7–10; 1989, Appendix Table 7–10; 1991, Appendix Table 6–7). Note that decline for Japan in 1980 corresponds to shift in basis of calculation.

V. *The Closing Gaps*

The period since the middle 1950s has seen a dramatic narrowing of the economic and technological gaps among the major industrial powers, largely ending a leadership position nearly a century old. The U.S lead in high technology industries was a more recent phenomenon. Interestingly, it appears to have held up better than the general U.S. economic lead. Figure 10 shows the share of the major industrial nations in exports of high technology products over the period since 1965. Contrary to popular belief the U.S. share has diminished only slightly. The major change has been in the position of Japan relative to Europe, although the latest revised figures soften the picture. Figure 11 shows U.S. exports and imports of high technology products since 1970. It has been the growth of U.S. imports, particularly since 1983, not a decline of export performance, that has been the principal source of the erosion of the U.S. high technology trade balance.

The data on patents reflect the same pattern. Since 1970 there has been a significant decline in the share of patents taken out in the U.S. assigned to Americans. However, a large part of this decline reflects a rise in the fraction of inventions originating in other countries that are patented in the United States. From the middle 1960s to the middle 1980s the share of all world patents given to Americans has been relatively constant. Japan's share has risen dramatically, mainly at the expense of Europe. Many analysts have noted that U.S. patenting has shown an absolute decline

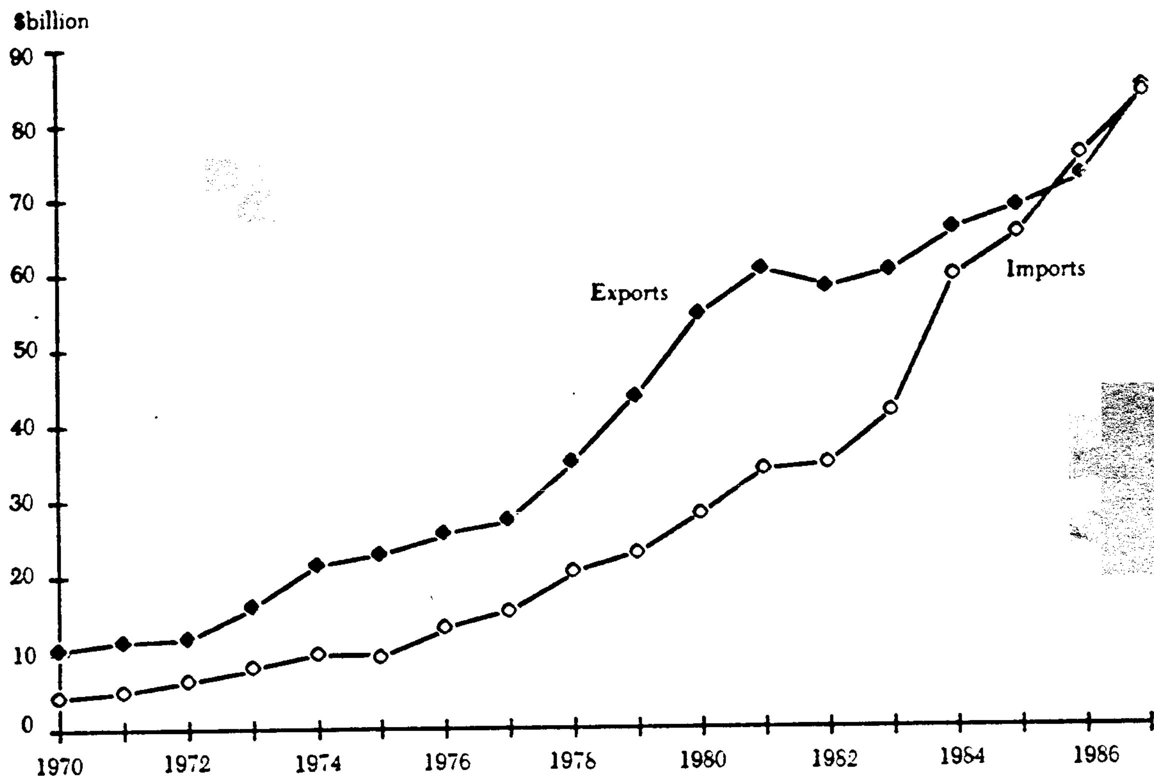

Figure 11. U.S. Trade in High-Technology Products, 1970–1987

Source: U.S. National Science Board (1989, Appendix Table 7–14)

since the late 1960s. That is so, but it is also true of the major European countries and the U.S. rate has partially recovered since 1980. We do not know what forces may account for these trends, but of the major industrial nations only Japan has experienced an increase in patenting (U.S. National Science Board 1991).

Within the group of industries in question, more fine-grained analysis displays a more variegated picture regarding U.S. performance. Between the middle 1960s and the middle 1980s, the U.S. export share held up well in aircraft, aircraft engines and turbines, computing and other office machinery, and in several classes of chemical products. The U.S. export share declined significantly in professional and scientific instruments, and in telecommunications. U.S. firms were routed in consumer electronics. The data on national patenting show a similar pattern. By and large U.S. export shares have persisted in industries where U.S. patenting has held up, and declined where patents by nationals elsewhere have risen relative to American patenting.

The definition of high technology industries is somewhat arbitrary in that it is tied to R&D intensity exceeding a particular level. A number of industries are excluded from the definition, whose product and process technologies are complex and sophisticated, and where technical advance has been significant. Automobiles, machine tools, and other kinds of machinery are examples. By and large U.S. export share and patenting have fallen significantly in these industries. Europe has done rather well. In contrast, the U.S. continues to be the export and patenting leader in many industries connected with agricultural products and others based on natural resources.

Thus beneath the surface of general productivity convergence, there is a much more variegated picture. U.S. performance continues to be strong in several of the most R&D intensive industries, and those connected to natural resources. It has declined in many of the industries—like automobiles, consumer electrical products, and steel making—where the U.S. had a dominant world position since the late nineteenth century. The interesting question, of course, is how this broad convergence came about. What were the forces behind it?

We would highlight four different developments. First, the decline in transportation costs and trade barriers has greatly expanded the flow of world trade, eroding the advantages in market size and raw material costs that U.S.-based firms used to have. Second, technology has become much more generally accessible to those with the requisite skills and willing to make the required investments, and hence much less respecting of firm and national boundaries than had been the case earlier. Third, the other major industrial powers significantly increased the fraction of their work forces trained in science and engineering, and the fraction of their GNP allocated to research and development, thus establishing strong indigenous competence to exploit technologies from abroad, as well as to create new technology. Indeed, by 1980 a number of countries were outspending the United States in nonmilitary R&D as a fraction of GNP. This is important, because the fourth major factor behind convergence was, in our view, a decline in the importance of spillover from military R&D into civilian technology.

The period since 1960 has seen a significant rise in the percentage of manufactured products exported and imported in virtually all major industrial countries. Between 1960 and 1980, U.S. imports roughly doubled as a fraction of GNP. In France, Germany, and the U.K. taken as a group, the ratio of imports to GNP increased by about fifty percent. It grew by a quarter in Japan. All of these ratios were substantially higher for manufacturing alone. Thus, over this period, efficient companies producing attractive products increasingly faced a world rather than a national market. At the same time, trade in natural resources greatly expanded, and countries became less dependent on local materials. Postwar resource discoveries were far more dispersed around the globe than previously. Although the United States continued to be a large contributor to world mineral production, the country became a net importer of most major minerals, implying that the cost to industrial users was essentially the same as that in other countries. Thus the twin advantages long possessed by American mass producers—cheap raw materials and more-or-less exclusive access to the world's largest market, both have dissolved. Despite continuing fears of a return to protectionism, by the 1980s much of the world had largely become a common market.

At the same time, business has become increasingly international. Technologically progressive American companies had established European branches even in the 19th century, but the scale of overseas direct investment surged dramatically during the 1950s and 1960s. In *The American Challenge*, Servan Schreiber expressed concern that American companies were taking over the European economy at least as much by investing there as by exporting. By the late 1960s Europe was beginning to return the favor by establishing branches or buying plants in the United States. Recently Japanese companies have done the same, on a larger scale.

The internationalization of business has greatly complicated the interpretation of international trade statistics. For example, a nontrivial share of the rising U.S. imports in high technology industries mentioned above originate in foreign subsidiaries of U.S.-owned companies (Richard Langlois 1987, ch. 4). While the U.S. share of world manufacturing exports (low and middle tech as well as high tech) fell somewhat from the middle 1960s to the middle 1980s, the export share of U.S.-*owned* firms held up, with gains in exports from foreign branches matching declines in exports from U.S.-based plants (Robert Lipsey and Irving Kravis 1986).

The internationalization of trade and business has been part and parcel of the second postwar development that we want to highlight—the erosion of firm and national borders as barriers obstructing or channeling access to technology. Modern science has, from its beginnings, been an international activity. The ethos of science has for centuries stressed the public and international nature of scientific knowledge. British and French scientists continued to communicate during the Napoleonic wars, and attempts by national governments to define and keep separate a particular national science have often been condemned by the scientific community. Despite this ancient tradition, the real world of practical science has also displayed strong national elements, explicitly so in wartime, implicitly at other times in language, terminology, institutional structures, and objects of study.

In contrast to the universalist ethos of science, the notion that individuals and firms have proprietary rights to their inventions has been accepted for many centuries, and so too the idea that it is appropriate for a nation to gain advantage from the inventive work of its nationals. Nations have often tried to keep national technologies within their borders, however futile these efforts may often have been in many cases. Though technologists from different countries have communicated, and formed something of an international community, until recently the notion that best-practice technology was approachable by any nation with requisite resources was probably not correct. The technological advantage of the American mass market firms in industries like steel and automobiles did not derive from patents or well-protected secrets, but largely from experience gained well ahead of foreigners because of differences in the economic environment. With firms all over the world facing a common market for products and inputs, the forces that used to provide U.S. companies with incentives to get into certain technologies first have been largely eroded.

While the increasing similarity of economic environments may be the immediate reason for the convergence of technological capabilities, another important underlying development in the post World War II era is that many technologies became more like sciences than before. Earlier we described the particular characteristics of science-based industries like chemical products and electronics. It is noteworthy that patents in these industries (and recently in bio technology) have tended to cite scientific literature to a far greater extent than do patents in fields like steel and automobiles. Since 1960, however the number of citations to scientific literature in patents has increased significantly in almost all technological fields, including steel and autos (Narin and Noma 1985). In contrast to an earlier era, a larger proportion of the generic knowledge relevant to a technology now is written down, published in journals, discussed at national and international meetings, taught in schools of engineering and applied science.

Internationalization of business is an important part of this story. It is not just that foreigners can learn what American engineers can learn by going to American universities. European engineers can observe American technology in operation in their home countries, and purchase operating American firms. Companies like IBM have industrial research laboratories in a number of different countries, each employing a mix of nationals. In turn, scientists from IBM and scientists from Phillips, and Fujitsu, meet at conferences and exchange papers. Employees often move across national borders, within a firm or between firms. These are truly international networks, involving highly trained scientists and engineers, employed in universities and in industry, undertaking significant R&D efforts. The technologies emerging from such networks no longer have geographic roots, because horizons have become global, and because material resource inputs more generally have declined in importance, relative to processing.

Generic technological knowledge, of the sort taught in graduate school, written down in books and articles, and exchanged among high-level professionals, does have strong public good attributes. However, access is limited to those with the requisite training, and in many cases only someone who is actually doing research in a particular field can understand the significance of publications in that field. To take industrial advantage of generic knowledge, or technology that is licensed from another company, or more generally to understand what another company has done and how, generally requires significant inputs of trained scientists and engineers, plus research and development expenditure aimed to tailor what has been learned to the specific relevant uses (Pavitt 1987; Nelson and Winter 1982; Nelson 1988).

The other major industrial nations have, with a lag, followed the United States in making those big investments in education and training, and R&D. The convergence in scientists and engineers in R&D as a fraction of the workforce, and in R&D as a fraction of GNP, shown in Figures 8 and 9, is an essential part of, and a complement to, the internationalization of technology. Definitions of these concepts are subject to continuing debate and change, and the most recent revisions by the National Science board put the current U.S. position in a more favorable light. By any definitions, however, the direction of change is clear. The U.S. lead in the early 1960s is striking. Convergence has occurred among those nations with modern educational systems, strong internal scientific and engineering communities, and sophisticated industrial enterprises. Nations without these attributes have tended to fall farther and farther behind the frontiers. There are now few important technological secrets, but it takes major investments of many kinds to command a technology.

Military technology has had a somewhat different history. The major military powers, prominently the U.S., continue to bend strong efforts to prevent military technology from leaking away to potentially hostile nations, or to nations who might serve as a conduit to hostile nations. But just as the political context of world conflict has changed with the end of the cold war, the economic context has altered completely. While American dominance of the frontiers of military technology gave us significant civilian technology advantages during the 1950s and 1960s, today it buys us little outside the military sphere. In terms of access to technology that affects productivity in industry broadly defined, it does not hurt the Europeans or the Japanese that American companies are engaged in military R&D to a much greater extent than they are, and that access to that technology is difficult if not closed.

There are several reasons for the diminished importance of military R&D as a source of technological advantage outside the military field. First, while initially civilian demands for computers, semi-conductors, and jet aircraft had lagged behind military demands, by the mid-1960s the civilian market for these products was as large or larger than the military; and in many dimensions, the performance demanded by the civilian market was actually higher. Companies responded by mounting their own R&D projects to meet these demands. Indeed, a strong case can be made that from the late 1960s the major direction of "spillover" was from the civil to the military. Thus the military bought the KC 10 as its tanker of choice, a plane that grew out of the McDonnel-Douglas DC 10, designed by the company for use by commercial airlines.

At the same time, military R&D increasingly focused on areas where its needs were specialized, engaging in specific product development efforts as contrasted with broadly applicable research. The percentage of military R&D that went into research and experimental development has diminished significantly. With the end of the cold war, the outlook is for further decline in military R&D along with military spending more generally, but at this point we do not foresee dire consequences for American technology as a result.

VI. *Conclusion*

Let us recapitulate. We have argued that the postwar American technological lead had two conceptually distinct components. There was, first of all, the long standing strength in mass production industries that grew out of unique conditions of resource abundance and large market size. There was, second, a lead in "high technology" industries that was new and stemmed from investments in higher education and in research and development, far surpassing the levels of other countries at that time. Several factors lay behind the erosion of these twin leads. The most basic of these is that over the post World War II era, commodity and resource trade, business and finance, and technological communities, have all become increasingly transnational rather than national.

In his now classic 1986 article on convergence, Abramovitz distinguished between two variables influencing the extent to which (firms in) countries that are technologically behind a leader are able to catch up. One of these was "opportunity." The other was "social capabilities." Abramovitz noted that while the U.S. was the clear productivity leader from before World War II, there is little evidence of other countries doing much "catching up" prior to the post World War II era. Our arguments above attempt to flesh out the reasons for this delay. Other countries with the requisite social capabilities, principally then in Europe, lacked the market size and resource availabilities that lay behind the U.S. advantage in mass production industries, and barriers to external trade foreclosed the possibility of replicating the U.S. path on an international basis. Until trade barriers came down after World War II, the "opportunities" really were not there. The reason for persistence of the U.S. lead in "high tech" industry was somewhat different. Until the European nations and Japan made the requisite massive investments in scientific and engineering education, and in R&D, they lacked the "social capability" to catch up in these industries.

It is not our intention here to resolve the full range of issues raised in the convergence literature. We do have two related observations. First, much of the literature treats technology as if it were a "public good," allowing only that there may be some friction in moving it around. Instead, as we have argued, much of what is involved in mastering a technology is organization-specific investment and learning. Hands-on technological capability is more like a private good than a public good. For that reason, if the economic conditions and incentives facing firms in different countries differ significantly, then firms in one country will require technological capabilities very different from those in another country. This argument is far removed from the conventional distinction according to which firms simply "choose" to employ different techniques (e.g., factor mixes) within a common underlying technology. To the extent that our interpretation holds, there is nothing automatic about convergence.

Secondly, however, since the 1950s the world has been changing so that, as a reduced form, the convergence model looks more and more plausible. In our view, it is the internationalization of trade, business, and generic technology and the growing commonality of the economic environments of firms in different nations that have made it so.

We believe that the internationalization of trade, business, and technology is here to stay. This means that national borders mean much less than they used to regarding the flow of technology, at least among the nations that have made the now needed social investments in education and research facilities. National governments have been slow to recognize these new facts of life. Indeed, the last decade has seen a sharp increase in what has been called "techno-nationalism," policies launched by governments with the objective of giving their national firms a particular edge in an area of technology. Our argument is that these policies do not work very well any more. It is increasingly difficult to create new technology that will stay contained within national borders for very long in a world where technological sophistication is widespread and firms of many nationalities are ready to make the investment needed to exploit new generic technology.

A closely related observation is that a well-educated labor force, with a strong cadre of university trained engineers and scientists at the top, is now a requirement for membership in the "convergence club." This is not to denigrate the continued importance of hands-on learning by doing and using, but in modern technologies this is not sufficient. It is no accident that countries like Korea and Taiwan, which have been gaining so rapidly on the world leaders, now have populations where secondary education is close to universal for new entrants to the work force, and where a significant fraction of the secondary school graduates go on to university training (Baumol, Blackman, and Wolff 1989; Barro 1991).

In our introduction we acknowledged another interpretation of convergence—that the trends reflect a growing incapacity of the American economy, and foreshadow the United States falling behind Japan, and perhaps Germany, as Great Britain fell behind the new leading economies at the turn of the last century. While we argue that the principal factor driving convergence over the last quarter century has been internationalization, we do not dismiss the possibility that the United States may be in the process of slipping into second, third, or fifth rank in productivity and per capita income, and in terms of mastering the application of several important technologies. Although the forces that now bind together nations with sufficient "social capabilities" are far stronger than they were in the past, there is certainly room for variance within that group. If the notion of social capability includes, not merely the educational levels at leading universities and research laboratories, but the social and political processes affecting the educational system, transportation and communications networks, and the legal and regulatory apparatus of federal and state governments, then it is entirely possible that a once-dominant nation may slip into social paralysis and decline. The distressing examples of Britain and Argentina are often cited, and Robert Reich (1991) argues that the U.S. is in danger of a similar fate.

To enter this question would require us to survey several additional bodies of literature, and we cannot do that here. There is, first, the puzzle of the extraordinarily slow growth rate of U.S. per worker productivity, per capita income, and total factor productivity, since the early 1970s. There is, second, the question of the national rate of savings and its link to investment: despite the increased flows of financial and direct foreign investment, it is still true to a considerable extent that a nation's volume of investment is closely related to its own flow of savings (George Hatsopoulos, Paul Krugman, and Lawrence Summers 1988), and that the growth of productivity is linked to capital investment (Landau 1990). Third, there is the literature proposing that the U.S. has lagged *because* it was the pioneer of older forms of corporate organization, which have now been made obsolete by radically different ways of organizing companies and political economies (e.g., Freeman 1987; Dertouzos et al. 1989; Lazonick 1990). These and other vital issues are beyond the scope of this article. But none of them impinge upon our basic argument, that the advanced nations of the world have come to share a common technology.

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